

Clumping in Hot Star Winds
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Clumping in the winds of O-type CSPNs

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Recent studies of massive O-type stars present clear evidences of inhomogeneous and clumped winds. O-type (H-rich) central stars of planetary nebulae (CSPNs) are in some ways the low mass–low luminosity analogous of those massive stars. In this contribution, we present preliminary results of our on-going multi-wavelength (FUV, UV and optical) study of the winds of Galactic CSPNs. Particular emphasis will be given to the clumping factors derived by means of optical lines (H α and HeII 4686) and “classic” FUV (and UV) lines.

1 Introduction

H-rich O-type central stars of planetary nebulae (CSPNs) are “downscaled” versions of massive O-type stars, at least with respect to their physical properties as derived from spectroscopic studies (see Kudritzki et al. 2006 and references therein). In the canonical picture of a planetary nebula, the fast wind coming from the central star is extremely important for the structure of the nebula, as well as for the subsequent evolution of the star itself. So far, the analysis of these winds have been based on sophisticated non-LTE models under the consideration of homogeneous winds (Kudritzki et al. 1997; Pauldrach et al. 2004). However, this assumption seems to be unrealistic, as could be suspected from recent studies of the winds of their massive (false) relatives (see A. Fullerton, J.C. Bouret, J. Puls or F. Najarro, this volume). Moreover, independent hints of the presence of inhomogeneous winds have been presented for the Of-type CSPN NGC 6543: first, the detection of X-ray emission coming from the central star (Chu et al. 2001), that could be only explained as the result of the presence of shocks in the stellar wind (in analogy with massive O-stars) and, secondly, the detection of discrete absorption components in FUV/UV profiles (see the contribution of R. Prinja in these proceedings).

Very recently, we have re-analyzed the optical spectra of a sample of CSPNs by means of non-LTE models atmospheres with inhomogeneous winds (Kudritzki et al. 2006), computed with FASTWIND (Puls et al. 2005). It was possible to estimate wind clumping properties for some of the targets in the sample, using a novel technique based on the relative strength of H α and HeII 4686 (see below). In order to check these results, and also to extend the analysis to other O-type CSPNs, we started a program aimed at the quantitative analysis of their ultraviolet spectra. In the following, we present (some) results of this complementary FUV/UV study on the winds of these objects.

2 Spectroscopy of CSPNs

Due to space constraints, we will not discuss the methodology followed in the analysis. The reader is referred to any of the many works published in recent years on quantitative spectroscopy techniques of massive stars. We will just provide some detail concerning clumping assumptions.

Regarding the model atmosphere codes, we used FASTWIND for the optical analysis, and CMFGEN (Hillier & Miller 1998) for the FUV/UV analysis. Clumping is treated presently in both codes under the *micro-clumping* formalism, i.e. *small-scale* density inhomogeneities in the wind redistribute the matter into clumps of enhanced density, embedded in an almost void (inter-clump) medium. Clumping is then characterized in the models by the *clumping factor* f_{cl} , which represents the overdensity in the clumps with respect to the smooth medium $\rho_{cl} = f_{cl} \rho$. Under the current assumptions, f_{cl} corresponds to the inverse of the volume filling factor.

2.1 Optical analysis

The analysis of the optical spectra has been presented by Kudritzki et al. (2006). With regard to the distribution of the clumping, we assumed a constant clumping factor f_{cl} for velocities larger than twice the characteristic isothermal speed of sound, and unity for lower velocities. This clumping distribution is basically equivalent to an exponential law rising (almost) at the base of the wind.

Below $T_{eff} \sim 37\text{--}36$ kK (depending on the gravity) He II becomes the dominant ionization stage, thus the lines’ optical depths present a linear dependence with density. On the other hand, neutral hydrogen is a trace ion at these T_{eff} s, hence its lines depend on ρ^2 . Therefore, it would be possible to estimate wind clumping factors by comparing the relative strengths of H and HeII lines with significant wind contribution. In the optical domain, H α and

HeII 4686 are the lines of choice. Using this concept, Kudritzki et al. (2006) estimated the clumping factors for three CSPNs, ranging from 1 to 50 (see Tab. 1). This same technique has been recently applied by Hultsch et al. (2007) to a sample of CSPNs in the Galactic Bulge.

Table 1: Parameters derived from the analysis of the optical spectra.

ID	Teff (kK)	log g (dex)	f_{cl}	$\log \dot{M}$ ($M_{\odot} \text{ yr}^{-1}$)
IC 418	36	3.2	50	-7.43
Hen 2-108	34	3.4	1	-7.46
Hen 2-131	32	3.2	8	-6.88

2.2 FUV/UV analysis

It is a well known fact that there are differences regarding the derived parameters when analyzing optical or UV spectra. These differences are most likely linked to subtle differences in the preferred codes used in each spectral windows. Seeking for consistency, we used our FASTWIND models (the atmospheric structure, both pseudo-static photosphere and wind) as an input for CMFGEN. In such way, the density distribution used to synthesize the FUV/UV spectrum is the same that was used for the optical analysis. Nevertheless, some minor corrections have to be applied to the parameters derived from the optical analysis. In particular, and for the domain explored here, the SiIV 1063–74, CIII 1176 and SiIV 1394–1402 Å lines present a high sensitivity to Teff. In general, these lines require a reduction in Teff of ~ 1 –1.5 kK, within the uncertainties of the analysis.

Concerning clumping, we used the standard implementation in CMFGEN, an exponential law. As previously quoted, this is consistent with the constant clumping form used in the optical analysis, provided that the constant value is reached soon enough (fast rising). Only in a very limited number of tests we have tried a distribution with clumping vanishing (f_{cl} becoming unity) in the outer parts of the wind (F. Najarro, this volume).

We display in Fig. 1 line profiles for two different cases, IC 418, for which we could infer clumping from the optical analysis, and IC 4593, a CSPN too hot to use the H α –HeII 4686 method. For each star, three different lines are presented: the bluest component of the PIV 1118–28 doublet, HeII 1640 and NIV 1719. In the first case, these three lines change strongly when considering inhomogeneous wind models. For the second star, the HeII line does not change at all: at this high Teff, HeIII is the dominant ioniza-

tion stage, and hence HeII lines behave as H α with respect to wind clumping.

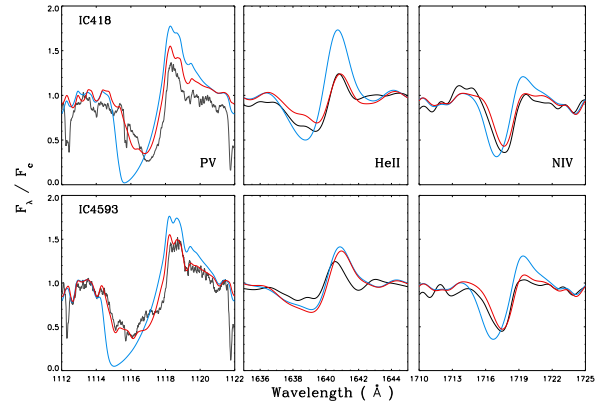


Figure 1: Observed (black) spectral lines compared with theoretical profiles for homogeneous (blue) and clumped (red) winds.

Other lines are also affected by clumping, such as SVI 933–45 Å. To a lesser degree, and most likely as a consequence of an “indirect” effect (due to the reduced \dot{M}), photospheric lines (FeV and OIV) display variations in the sense that the fits are improved when (wind) clumping is considered.

All the CSPNs in our sample for which FUV data (either FUSE, COPENICUS or TUES) are available present features that can be associated with the OVI 1032–38 Å lines. These *super-ionization* features (as well as NV 1238–42 Å) are related to X-rays, usually explained as produced by shocks in the winds. We have tried to model these features in some (few) cases, to investigate the sensitivity of the primary clumping diagnostics to the presence of X-rays. While we did not manage to produce completely satisfactory fits, these tests have shown that all the clumping indicators are insensitive to the presence of X-rays (note that present implementations of X-rays in model atmosphere codes are very crude).

3 Discussion

While we have results presently for a handful of objects, there are a number of conclusions that can be drawn from this preliminary work. First, it seems to be possible to achieve good fits to FUV/UV spectra with the parameters derived from the optical analysis (see Fig. 2). The ability of reproducing simultaneously ultraviolet and optical ranges increases our confidence on that the physics considered in the models is a fair representation of the true one (i.e. we are not missing any important contribu-

tion). Secondly, FUV/UV clumping sensitive lines support f_{cl} values derived using $H\alpha$ – $HeII$ 4686 for the coolest objects. There is not an apparent reason why this method should not work also for massive O-stars in the appropriated T_{eff} – $\log g$ domain. Thirdly, and most important, CSPNs with very similar fundamental parameters have substantial differences in their clumping properties. To the best of our knowledge, this has not been found (yet) in the case of massive O-stars. Should this be confirmed, it would have tremendous implications for (theoretical) predictions of CSPNs mass-loss rates.

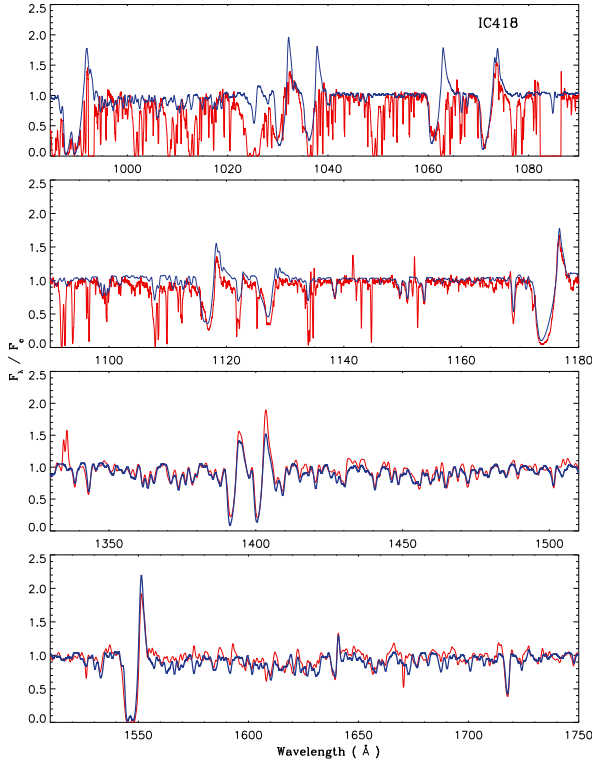


Figure 2: IC 418 FUSE and IUE data (red). A model including clumping ($f_{cl} = 50$) and X-rays ($\log L_x/L_\odot = -4.27$) is shown in blue. Note the heavy contamination of FUSE ranges by the medium surrounding the star.

There are a number of open issues related to the

comparison of the derived properties with the corresponding expected theoretical values, from the point of view of post-AGB evolution as well as from the radiatively driven wind (RDW) theory. First, for some of the objects we still derive uncomfortably high spectroscopic masses. Since these objects are evolving directly to the WD phase, CSPN masses above ~ 0.8 – $0.9 M_\odot$ (as derived for IC 418, Tc 1 and NGC 2392) seem unrealistic (WD mass distribution peaks around $\sim 0.6 M_\odot$). Secondly, the ratios of the measured wind terminal velocities to the derived escape velocities are in general higher than the values expected from the RDW theory. Increasing the masses will bring these ratios closer to the expected values, but this would badly affect the comparison with post-AGB evolutionary models, increasing the number of objects with extremely high spectroscopic mass.

At present, it is not clear where the solution to these two problems resides. Is there any important ingredient missing in our model atmospheres? As previously quoted, our ability to reproduce a wide spectral range (FUV/UV/optical) seems to argue against this possibility, although it cannot be completely ruled out. On the other hand, wind hydrodynamics are based on the assumption of smooth winds. Theoretical predictions have to be checked with the inclusion of clumped winds (deKoter and Kriticka, this volume).

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